The international scenario
Balloons, LiteBIRD, PIXIE, Millimetron

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on behalf of the Italian CMB community

Overview

- International scenario for instruments devoted to measurement of Temperature Anisotropy and Polarization of the Cosmic Microwave Background radiation

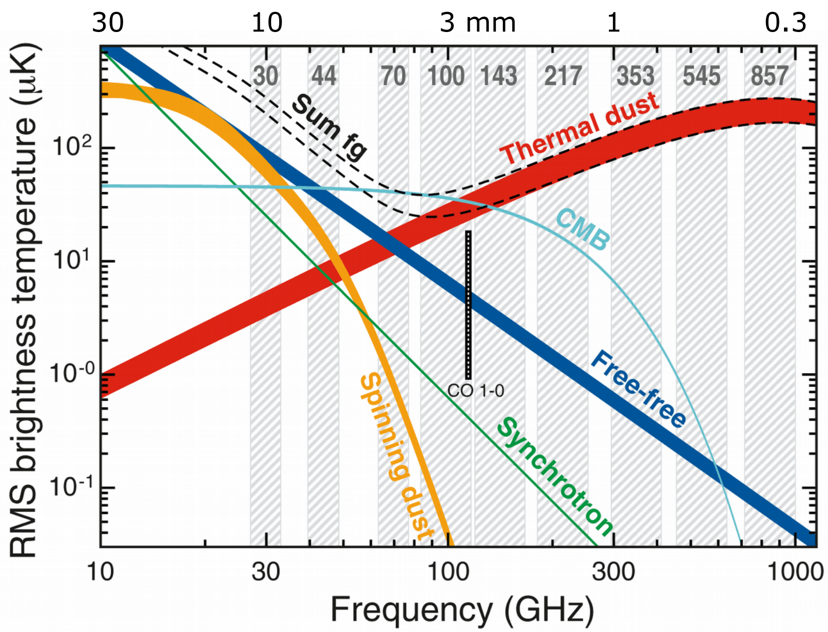
- Spectral bands
- Angular resolution
- Targets and Sensitivity

- Instruments
  - Ground
  - Balloon
  - Space

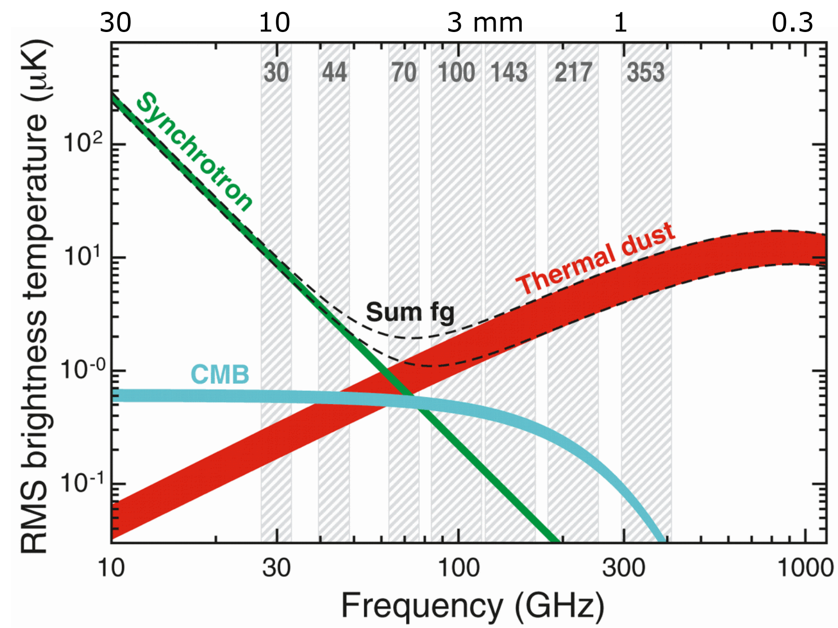
Spectral frequencies of interest

Diffuse emission in the microwave band:

Temperature (best 81-93% of sky)



Polarization (best 73-93% of sky)

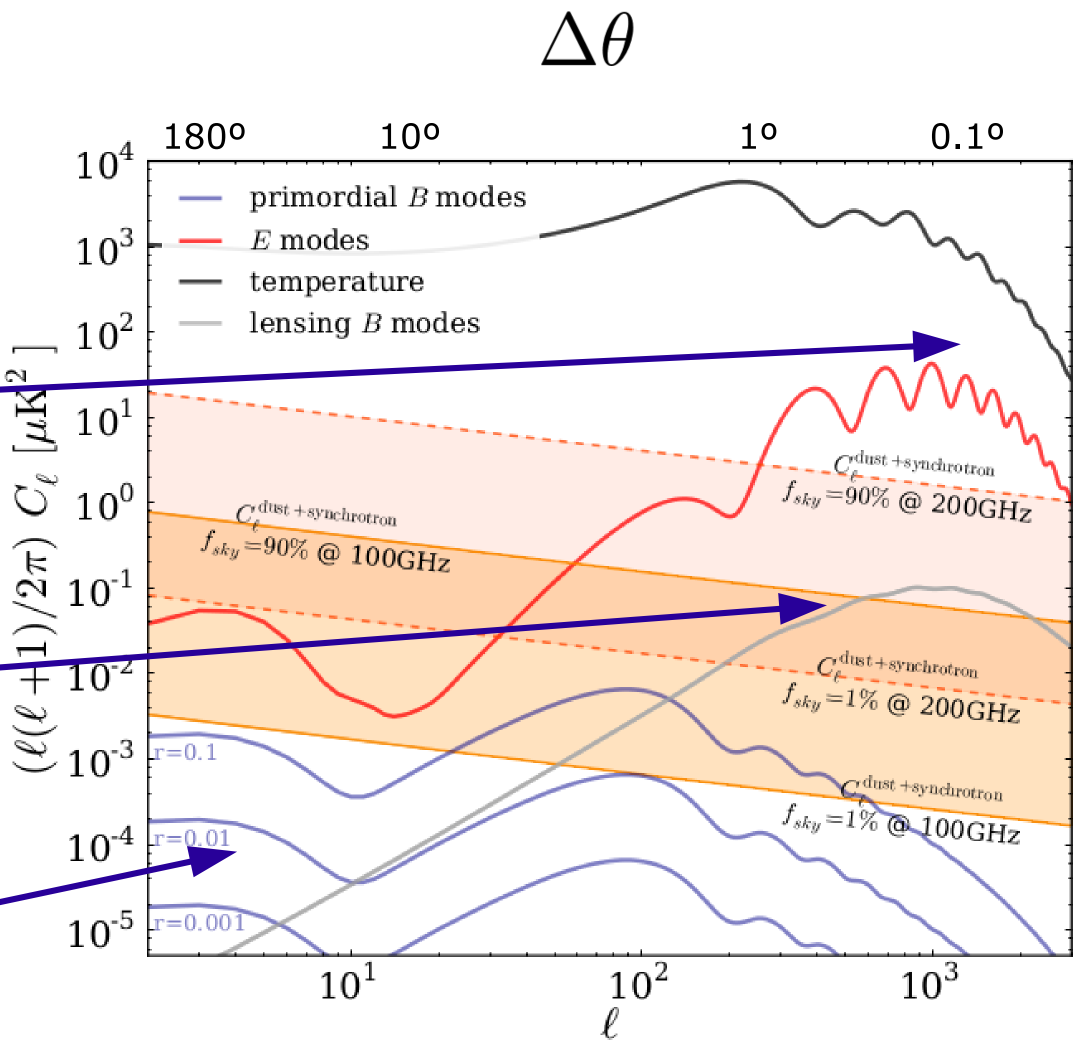


(Planck observation bands in shadow)

Angular scales of interest

Angular power spectra

Signal and contamination as a function of multipole number (inverse of angular scale)



Target signal 1

CMB anisotropy at small angular scales, to improve cosmological parameters determination

Target signal 2

Lensing effects due to distribution of large scale structures (dark matter)
Also measured by other probes
Signal well predicted

Target signal 3, B-mode

Inflationary gravitational waves
Not measured by other probes
Signal unknown

Inflationary Gravitational Waves – current data

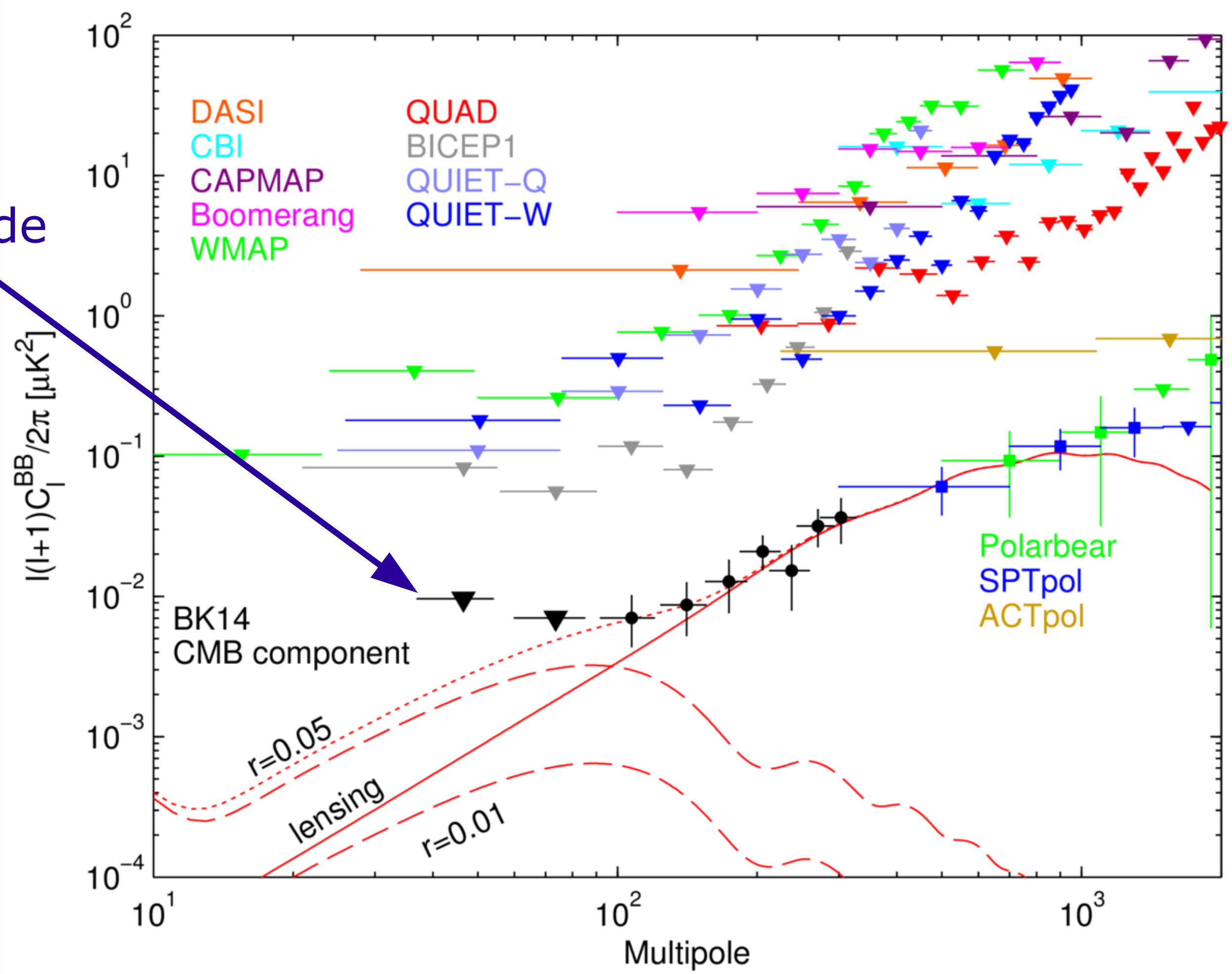
Target signal 3, B-mode

Inflationary gravitational waves
Not measured by other probes
Signal unknown

Current limit
(direct detection, 95% confidence)

$$r < 0.09$$

Phys. Rev. Lett. 116, 031302, 2015



Sensitivity to Inflationary Gravitational Waves

Following Kamionkowski & Kovetz, ARAA 2016, the **error** on the tensor to scalar ratio, in presence of noise and foreground can be approximated as a combination of:

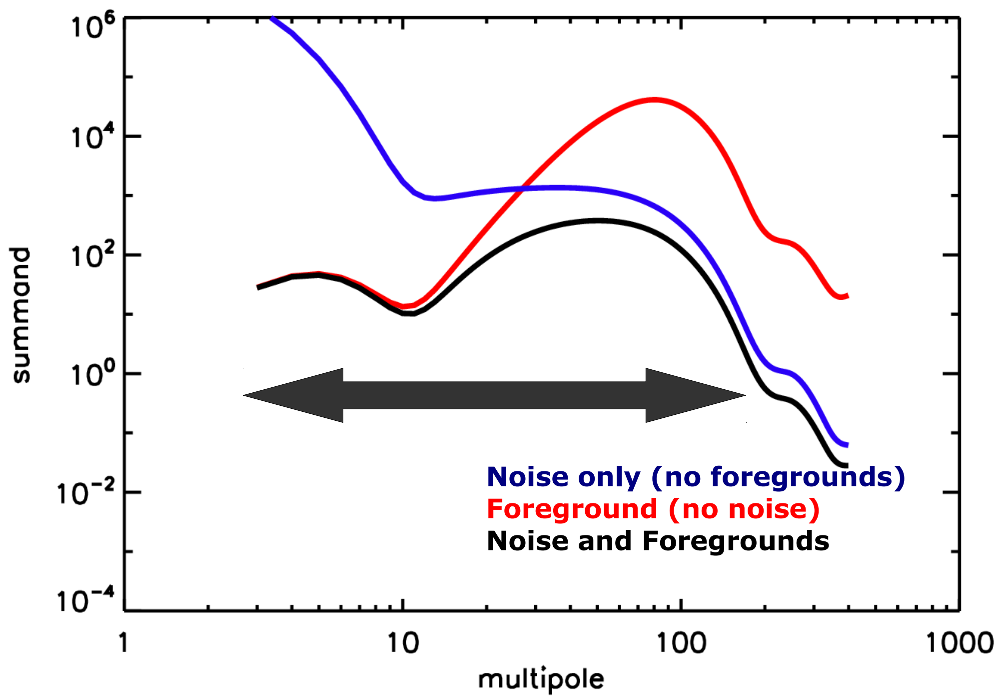
Noise

Lensing

foregrounds

$$\sigma_r \simeq \frac{0.1}{f_{\rm sky}} \sqrt{\frac{1}{\sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{(2\ell+1)}{2} \left(\frac{C_\ell^{\rm IWG}(r=0.1)}{C_\ell^{\rm fg}+C_\ell^{\rm n}+C_\ell^{\rm lens}} \right)^2}}$$

The higher the black curve the better



Correction of:
- foreground by a factor of 10 in amplitude
- lensing by a factor 3

Noise = 2 μK·arcmin

2-200 is the range to look at

Large scales to 0.5º

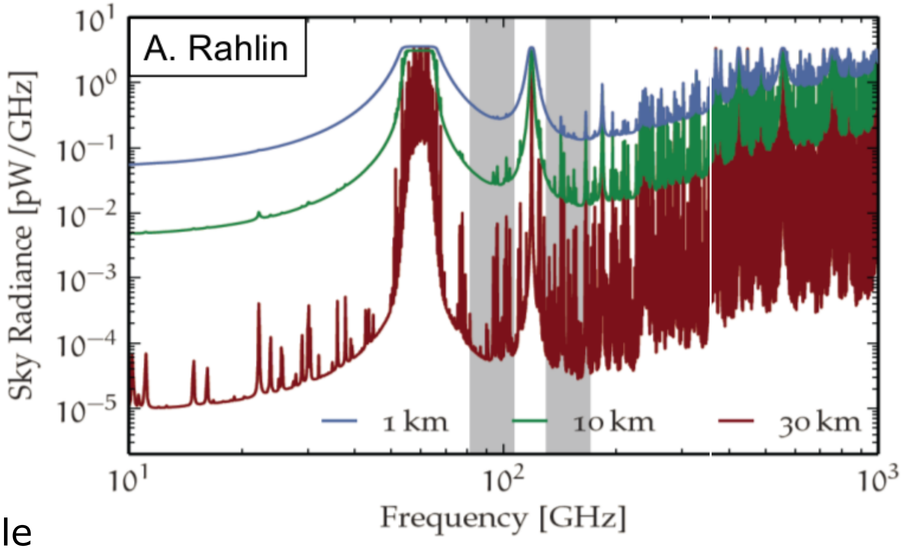
Smaller scales for lensing cleaning

The international community effort

1) **Ground**
- Mid-Large telescopes (up to 10 meters)
- Atmosphere limits instruments to low spectral frequencies (up to 150 GHz)
- Long integration time (years), low noise
- Requires "extreme" locations, dry and high:
  - Antarctica, Atacama, …

2) **Balloon**
- Smaller telescope (up to ~2m)
- Can go to higher frequencies
- Short integration time (2 weeks)
- High risk

3) **Satellite**
- Can go to higher frequencies
- Long integration time (years)
- Small telescope (up to ~2m), or deployable
- Cost



Ground based experiments – Europe

- **QUIJOTE**
  - Active in Tenerife
  - 0.5 – 1º resolution
  - Polarization sensitive: galaxy + deep survey

	MFI				TGI	FGI
Nominal frequency [GHz]	11	13	17	19	30	40
Bandwidth [GHz]	2	2	2	2	10	12
Number of horns	2	2	2	2	31	31
Channels per horn	4	4	4	4	4	4
Beam FWHM (°)	0.92	0.92	0.60	0.60	0.37	0.28
T_{sys} [K]	25	25	25	25	35	45
NEP [μK $s^{1/2}$]	559	559	559	559	44	52
Sensitivity [Jy $s^{1/2}$]	0.61	0.85	0.62	0.77	0.06	0.07

- **QUBIC** bolometric interferometer: in preparation (see presentation by S. Masi)

- **NIKA 2**
  - Active in IRAM Granada
  - High resolution
  - Galaxy clusters

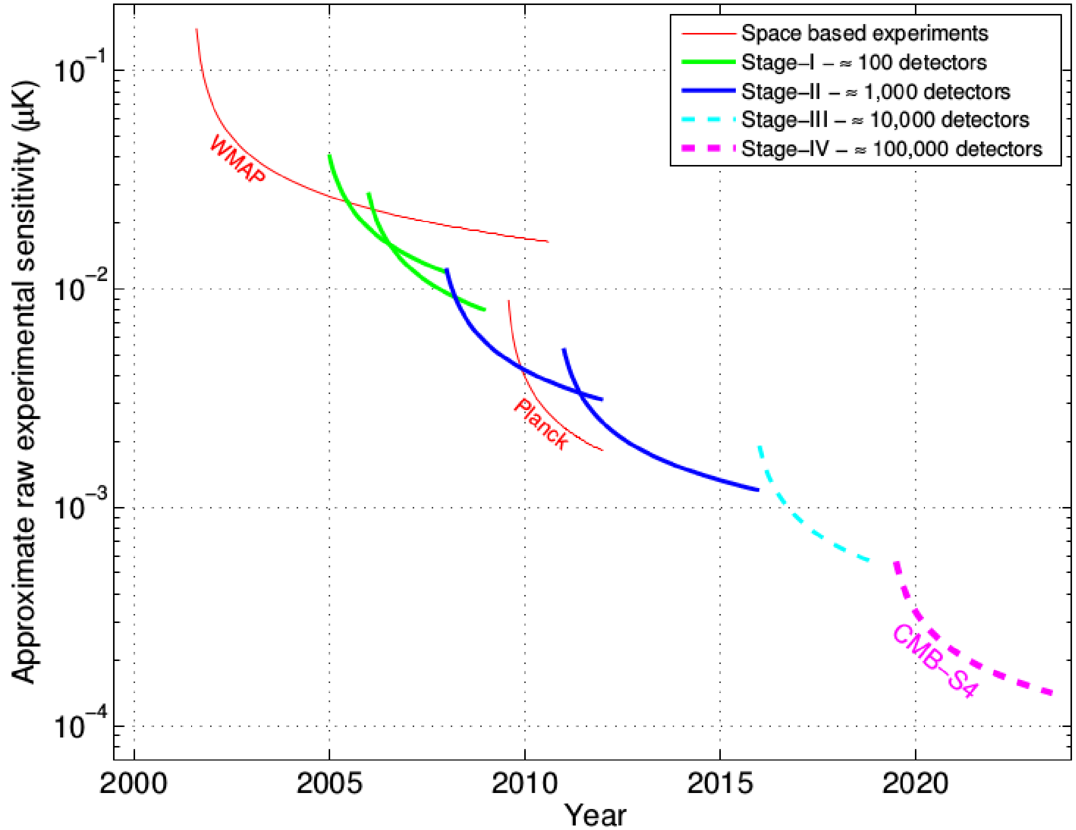
Wavelength [mm]	2.0	1.2	1.2(Q,U)
Frequency [GHz]	**150**	**260**	**260**
FWHM [arcsec]	18.5	11.0	11.0
Number of detectors	1000	2x2000	
FOV diameter [arcmin]	6.5	6.5	6.5
NEFD [mJy/beam·$s^{1/2}$] 90% of the FOV	10	15	30
Point Source Sensitivity 1 sigma one hour in the FOV [mJy]	0.18	0.26	0.53
Extended Source 1 sigma one hour in the FOV [MJy/sr per /beam]	0.042	0.180	0.350
Compton SZ *y* sensitivity 1 sigma one hour in the FOV per beam	40×10^{-6}		
Mapping speed [arcmin^2/mJy^2/hour]	1100	480	120

Main limit is the atmosphere. It precludes frequency above 150 GHz, and control of dust contamination

Ground based experiments – US

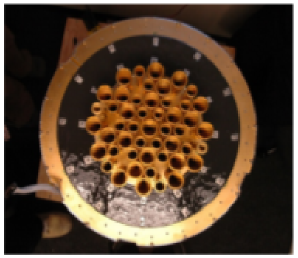
- The most massive efforts are the US **Stage 3** and **Stage 4** programs

  - Target
    - **σ(r) < 0.001**
  - Increase detector number
    - Up to 500’000 TES detectors
    - 40 – 240 GHz
    - Target noise 1 μK·arcmin
  - Increase detection sites
    - Antarctica
    - Atacama
    - Up to 50 % of the sky
  - Increase integration time
    - Next 10 years at least



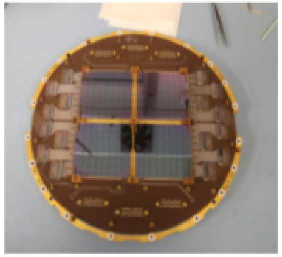
Ground based experiments – US – BICEP3

BICEP



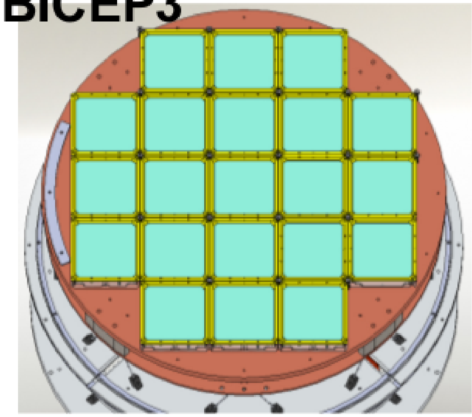
100 detectors
100 – 150 GHz

BICEP2



500 detectors
150 GHz

BICEP3



2560 detectors
95 GHz

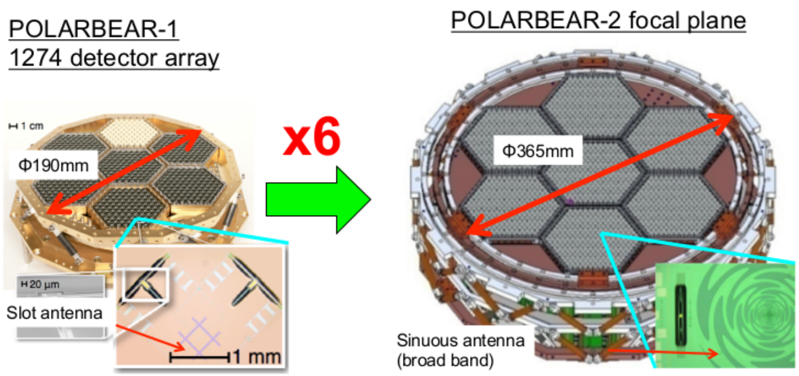
BICEP **Keck Array**

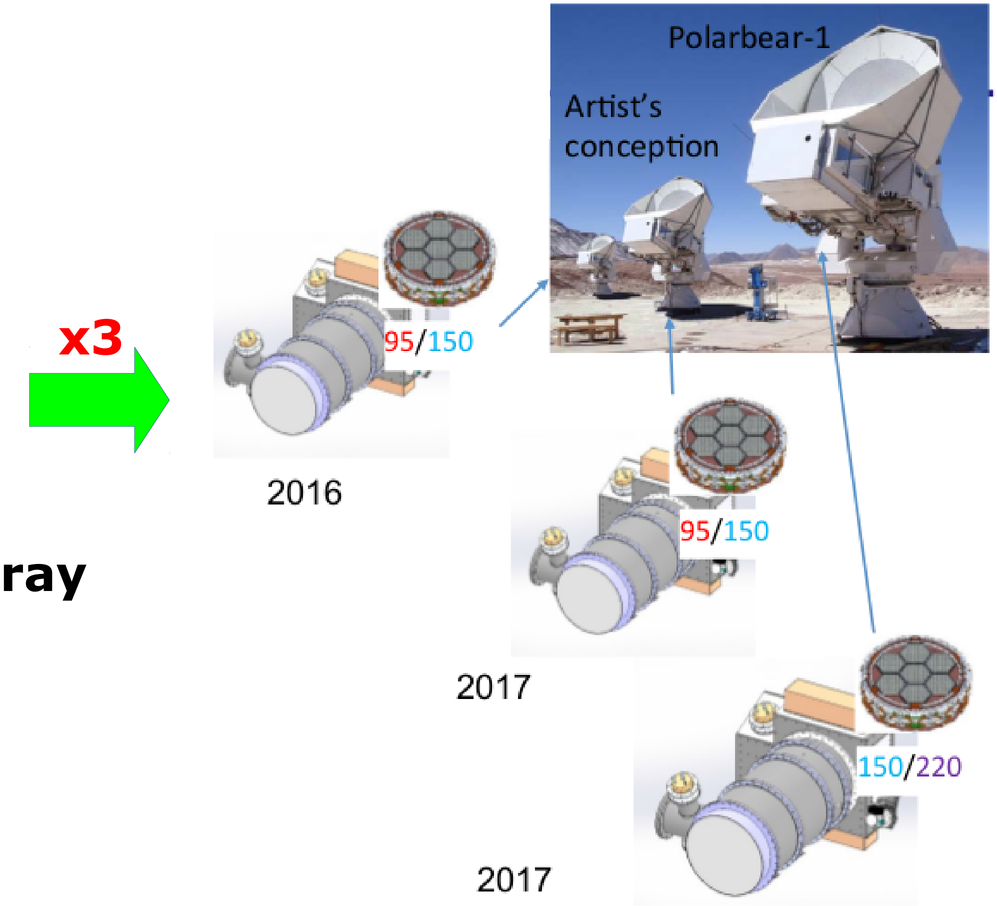
Target:

- Inflationary Gravitational Waves (B-mode)
- Large scales (~1º resolution)
- 90-150 GHz

- Similar: **CLASS**, **ABS**

Ground based experiments – US – PolarBear/SA





PolarBear, evolves in **Simons Array**

- Small scales (3.5' at 150 GHz)
- 95 – 150 – 220 GHz
- Up to 65% of sky observable
- Atacama
- 22'764 detectors

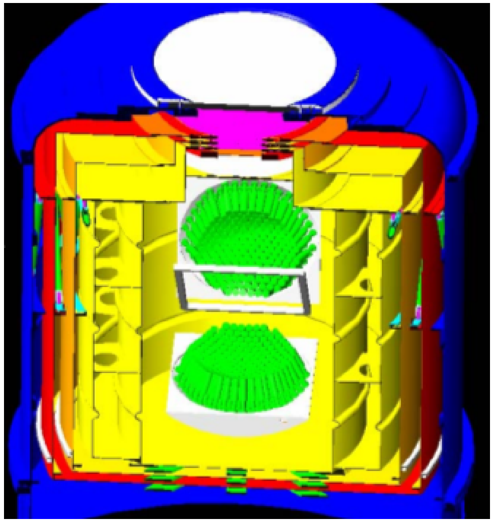
Similar: **SPT3G**, **Adv ACTPol**

Balloon experiments (Italy)

Italy (see Silvia Masi presentation)

OLIMPO

- No polarization
- Ready to go
- 140 – 210 – 345 – 480 GHz, with spectroscopic capability
- SZ effect
- high angular resolution

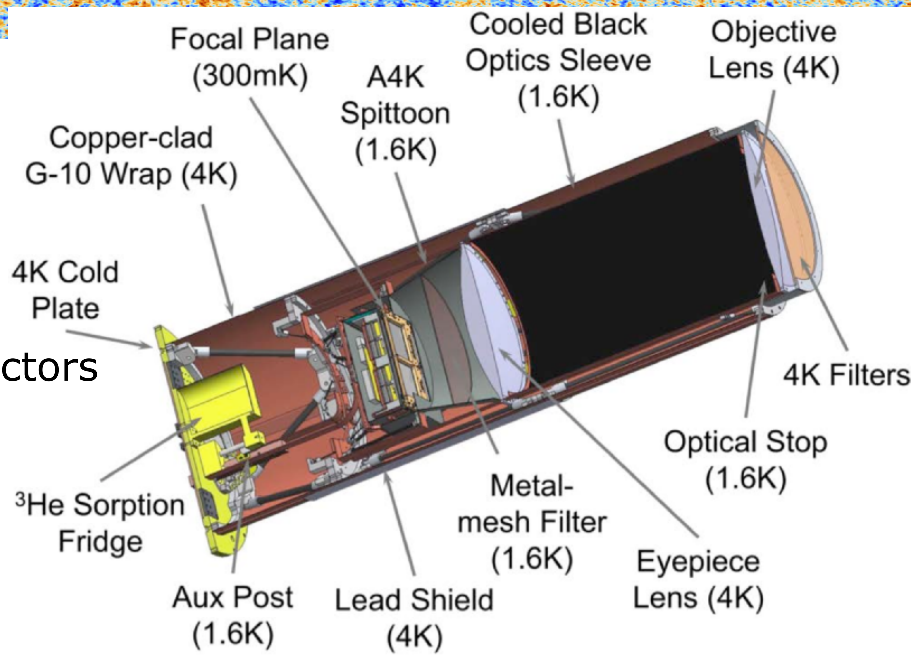


LSPE

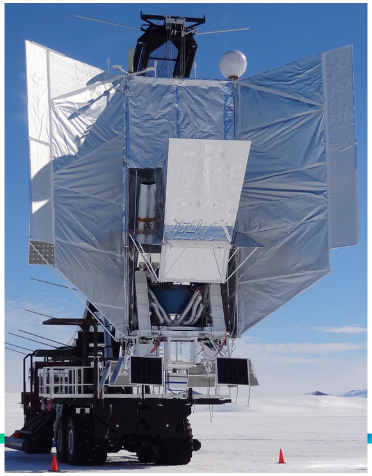
- Targeted to large scale of CMB polarization
- 40 – 220 – 240 GHz
- In preparation: launch planned for December 2017

Balloon experiments (US)

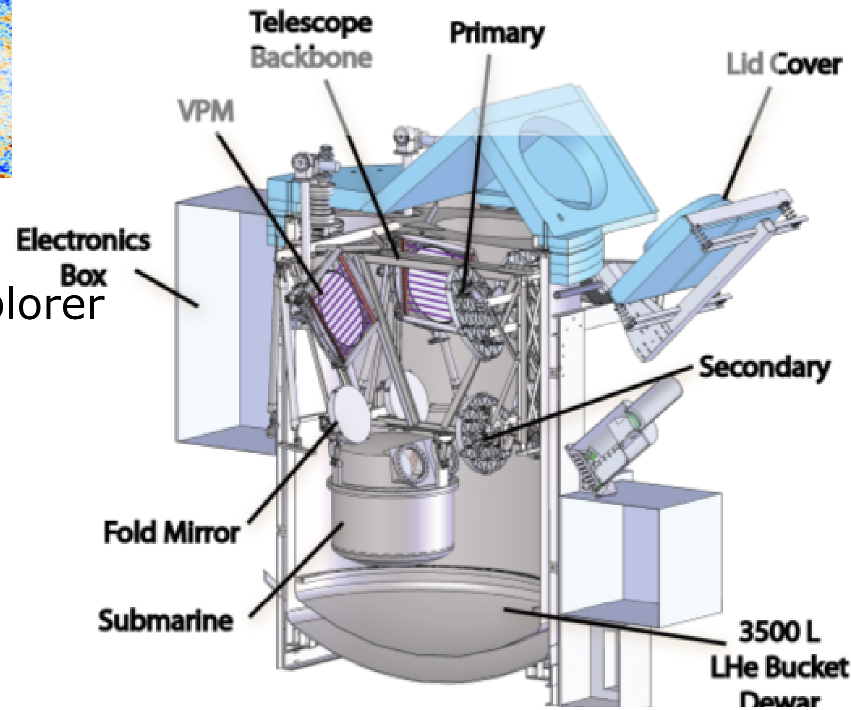
- **SPIDER** (Princeton)
  Launched in January 2015
  94 and 150 GHz bands
  10% sky observed, 2400 detectors
  Data analysis in progress
  Next flight in 2018



- **EbeX** (Minnesota)
  flown in 2012
  1200 detectors, 3 frequencies
  (150, 250 and 410 GHz)
  EBEX-10K, more than 10000 detectors
  4 bands (150, 220, 280 and 350 GHz)
  Not funded yet

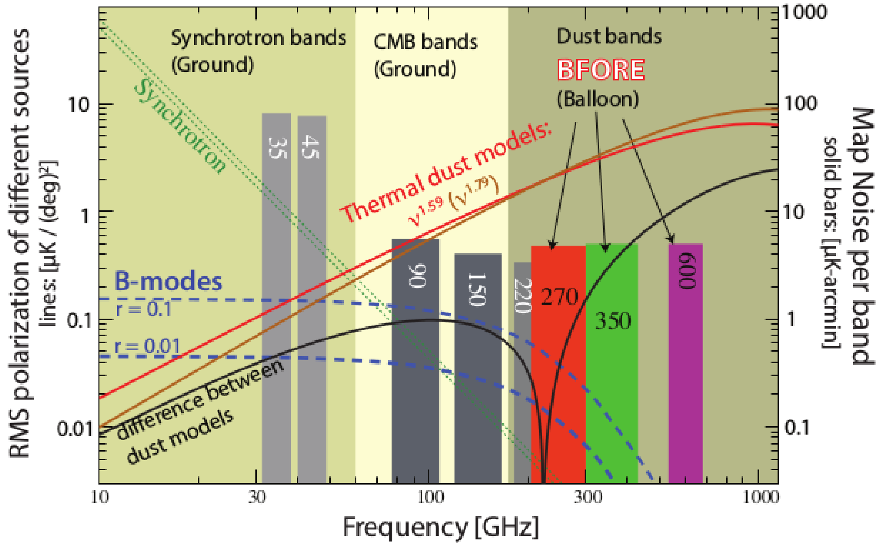


Balloon experiments (US)



- **PIPER** Primordial Inflation Polarization Explorer (Goddard)
  - 5120 TES bolometers in four 32 x 40 arrays
  - 1.5 K Optics with no warm window
  - variable-delay polarization modulator
  - Twin cryogenic telescopes
  - 200, 275, 350, and 600 GHz
    (Single frequency band per flight)
  - 8 flights, North and South hemisphere
  - Funded

- **B-FORE** (Arizona, U-Penn)
  - Measure of interstellar dust polarization
  - 270, 350, and 600 GHz
  - 10000 superconducting detectors
  - Based on the consolidated BLAST platform
  - Planned for Ultra-Long-Duration-Balloon
  - Not funded yet



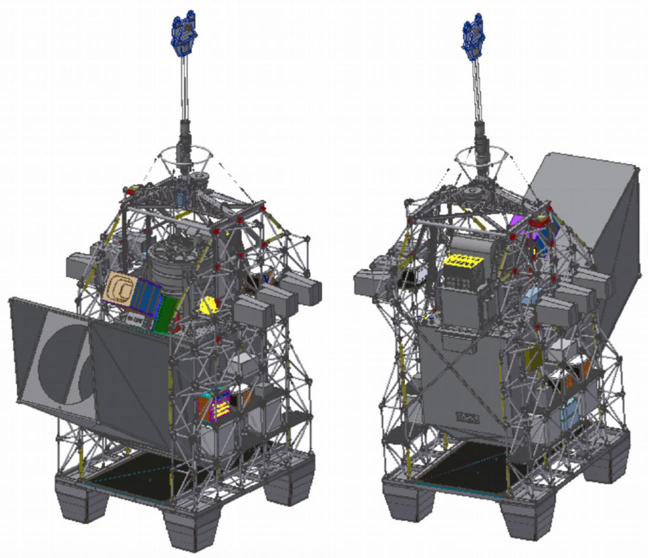
Balloon experiments (France)

- **Plan-B** (Grenoble, Toulouse, Paris)

  Measure of interstellar dust polarization

  Based on NIKA detectors (KIDs)

  Based on CNES PILOT gondola and primary mirror



Optics	
Primary mirror	M1 from PILOT (0.8m)
Instantaneous FoV (diameter)	3°(spec)
Polarization split	45° polariser at coldest temperature
Half-wave plate	4.2 K on magnetic bearing
Total transmission	40% (goal) & 20% (spec)
Angular resolution	5′(goal) & 7′(spec)
Detectors	
Total number of pixels	1900 (goal) & 980 (spec)
Fraction of good pixels	> 90%(goal) > 70%(spec)
Pixels size	From 2.3x2.3 to 3.2x3.2 mm
Frequency	One spectral band 450-700 GHz (baseline)
	Two bands 350-550 & 450-700 GHz (option)
NEP	Background NEP (goal); ×2.5 (spec)
Multiplexing ratio	250
KID frequencies	200-800MHz (depending on pixels size)
Cryogenics	
Base Temperature	120mK (goal) & 180mK (spec)
Power dissipated at 4K (amplifiers)	40mW
Power dissipated at base temperature	< 1μW
Half-wave plate rotation	10 Hz (goal) & 2.5 Hz (spec)
Polarization modulation	40 Hz (goal) & 10 Hz (spec)
Number of in/out RF lines	Between 4 and 8
Power readout electronics	160 W
Power cryostat (24h operation)	20 W

Sub orbital summary

Project	Location	Status	Frequencies	Detectors	Ang.Res.	Unicity	Science goals
ACT-pol/AdV-ACT	Atacama	Running	30, 40, 90, 150, 230	TES-TDM	high	Wide/deep/multifreq	r<0.01 + lensing
ABS	Atacama	Running	150	TES-TDM	low	HWP rotation test	TES+HWP tests
CLASS	Atacama	>2015	40, 90, 150, 220	TES-TDM	low	Very wide	r<0.02
POLARBEAR/SA	Atacama	Running	90, 150, 220	TES-FDM	high	First lensing	lensing
SPT-pol/SPT-3G	South Pole	Running	95, 150, 220	TES-FDM	high	Highest resolution	r<0.01 + lensing
BICEP3/Keck Array	South Pole	Running	95, 150, 220	TES-TDM	med	Very deep	r<0.01
QUBIC	Dome C	>2016	90, 150, 220	TES-TDM	med	Bol. interferometry	r<0.01
B-machine	White Mountain	Running	40→3-15	LNA	med	Low freq. monitor	low freq
GLP	Greenland	?	150, 210, 267	KIDs	med	KIDs	reion. peak
Ground-Bird	?	>2016	145, 220	KIDs	low	Technology for LB	reion. peak
MuSE	?	?	44, 95, 145, 225, 275	NTD-MM	low	Multimoded	reion. peak
QUIJOTE	Tenerife	Running	10, 20, 30, 40	LNA	low	Wide and multi-freq	r<0.05 + low freq
EBEX	LDB-Antarctica	2012→?	150, 250, 410	TES-FDM	med	First Baloon for TES	r<0.01
SPIDER	LDB-Antarctica	2014→2017	95, 150→+220	TES-TDM	med	Super sensitive	r<0.02
LSPE	LDB-Svalbard	>2016	43, 95, 150, 220, 250	TES-FDM-MM	low	Polar night flight	r<0.03 + reion. peak
Piper	Multple 1-day flights	>2015	200, 270, 350, 600	TES-TDM	med	Multi flight	r<0.01 + reion. peak
BFORE	LDB-Antarctica	>2018	270, 350, 600	TES+KIDs	high	Foreground machine	Foreground

Courtesy E. Battistelli

Satellite based experiments

Only space can provide at the same time:

- Full Sky
- Wide Frequency range
- Stability
- Long integration time

JAXA – LiteBIRD

Lite (light) satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection

JAXA mission to search for (and characterize) primordial gravitational waves

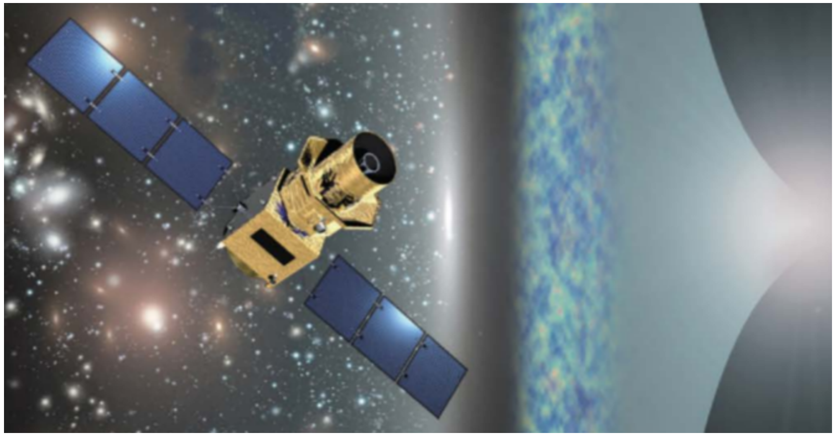
Method: Full-sky CMB polarization survey at degree angular scales

Full success: **$\sigma(r) < 0.001$** (total uncertainty on tensor-to-scalar ratio)

Statistical + Systematic + Foreground + Lensing + Observer bias

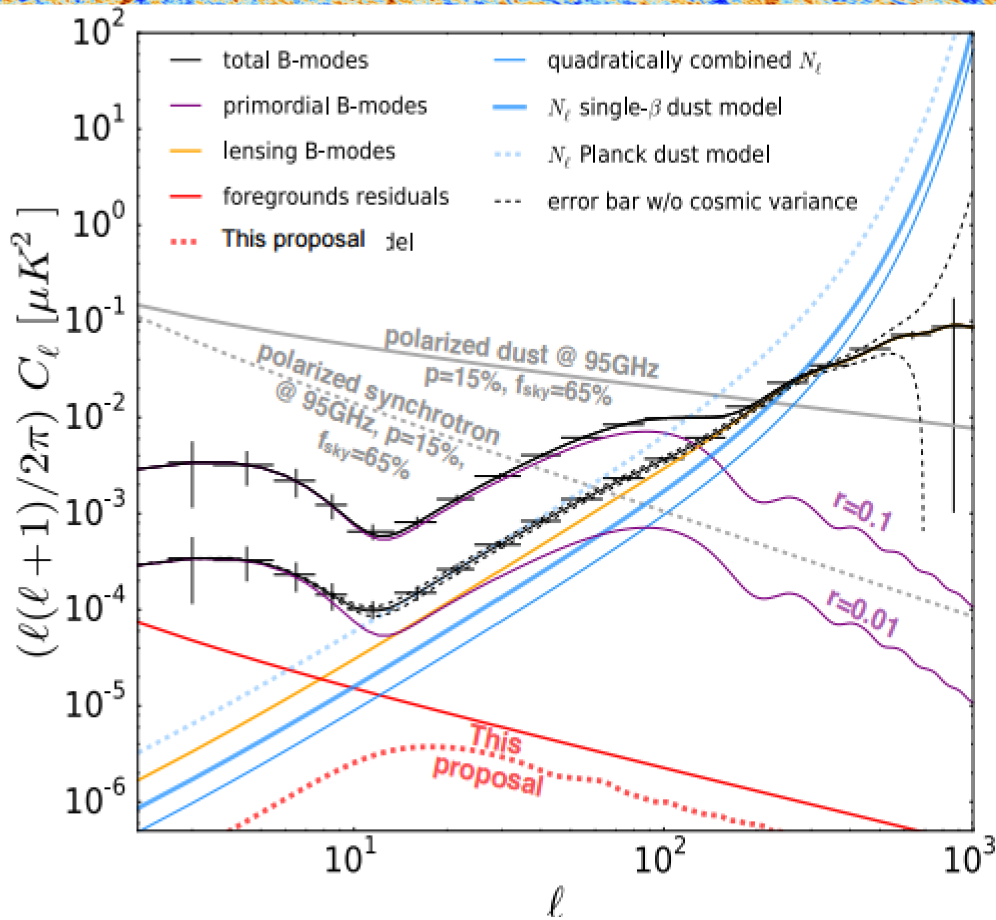
Status:

- Currently in Phase A
- Target launch 2020
- Observing time 3 years
- Multipole 2 – 200 (1^{o} resolution)
- Relies on ground measurements for full small scales



JAXA – LiteBIRD

- σ(r) = 0.45·10^{-3} for r = 0.01, including foreground removal*, cosmic variance and delensing**
- r < 0.4 x 10^{-3} (95% C.L.) for undetectably small r



Band (GHz)	Beam (ar-cmin)	NET ($\mu K\sqrt{s}$)	Pixels per wafer	N_{wf}	N_{bolo}	NET_{arr} ($\mu K\sqrt{s}$)	Sens. (μK·arcmin)	Sens. with margin (μK·arcmin)	Band
60	54.1	94	19	8	304	5.4	9.6	15.7	X
78	55.5	59	19	8	304	3.4	6.0	9.9	X
100	56.8	42	19	8	304	2.4	4.3	7.1	Y
140	40.5	37	37	5	370	1.9	3.4	5.6	Y
195	38.4	31	37	5	370	1.6	2.9	4.7	Z
280	37.7	38	37	5	370	2.0	3.5	5.7	Z
total					2022		1.6	2.6	

* Errard et al. 2011, Phys. Rev. D 84, 063005

** Sherwin & Schmittfull arXiv:1502.05356

NASA – PIXIE

Replace many detectors with 4 multimoded detectors

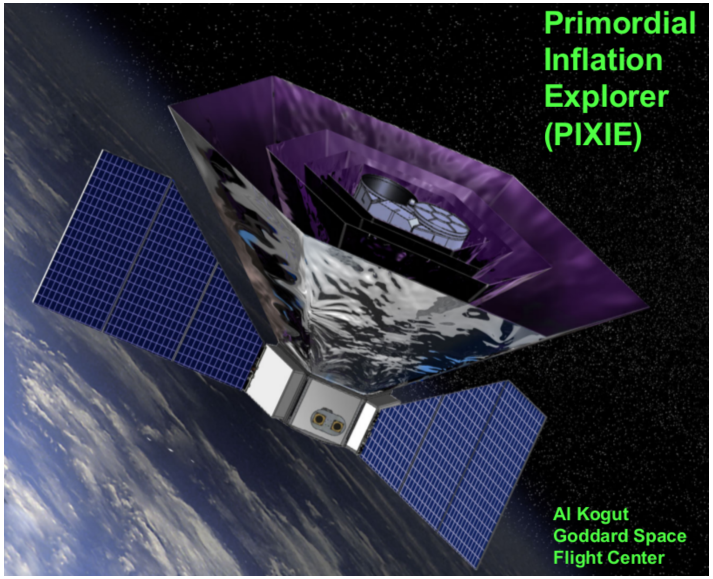
Entire instrument at 2.725 K

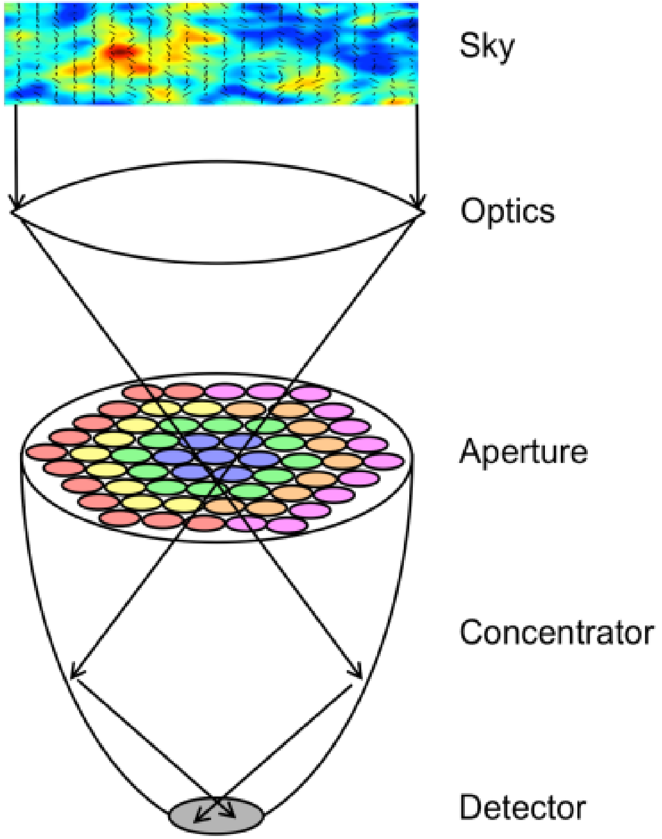
Replaces filters with Fourier Transform Spectrometer

400 channels 30-6000GHz

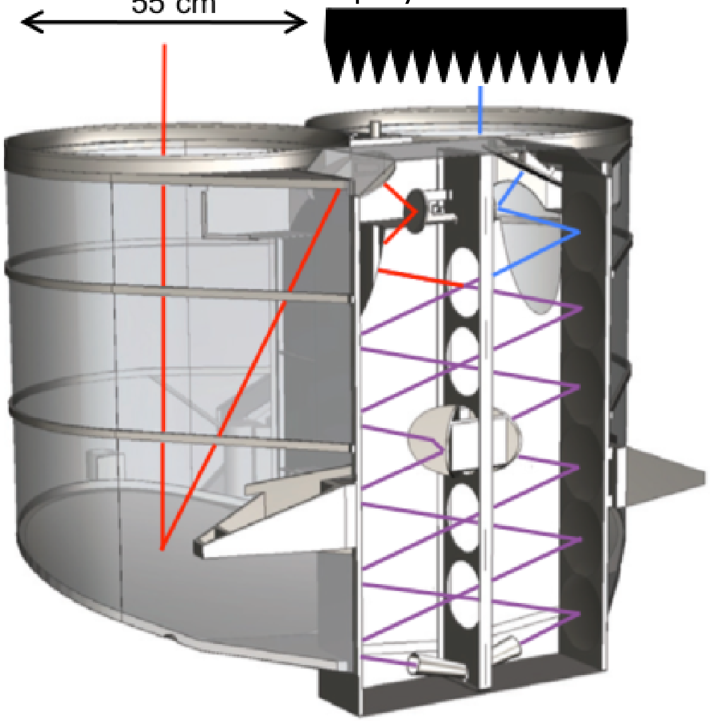
Spins at 4 RPM to sample Stokes Q/U

Not selected in 2011 (re-proposed in 2017)

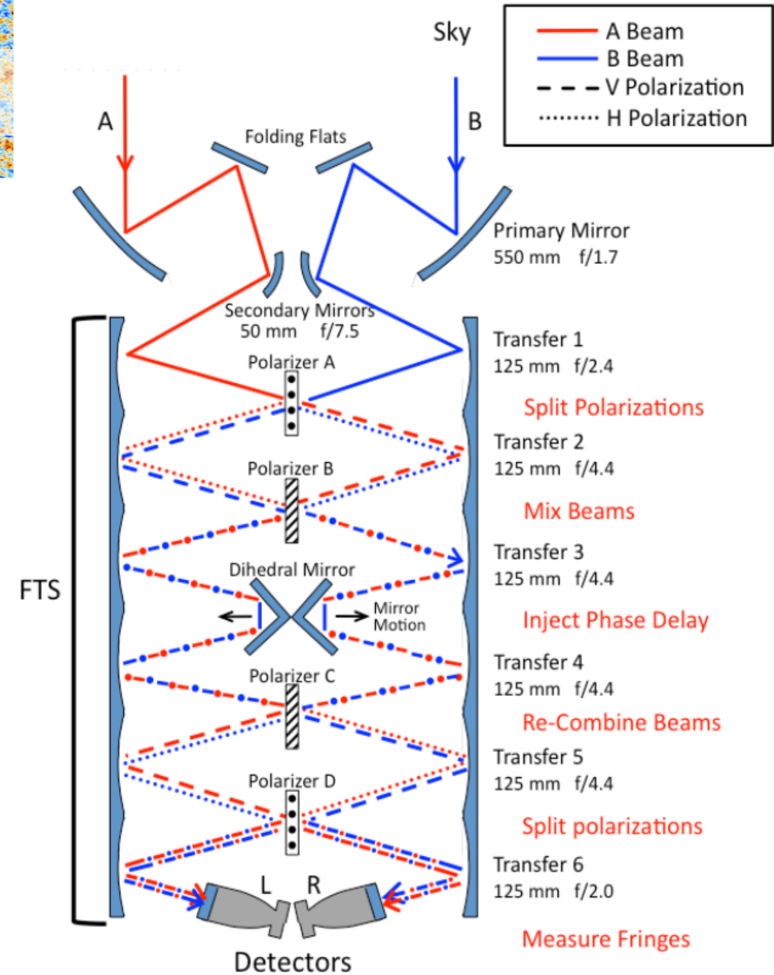




NASA – PIXIE



Parameter	Value
Primary Mirror Diam	550 mm
Etendu	4 cm^2 sr
Beam Diam	2.6° Tophat
Throughput	82%



Scientific goals:

B-mode: $\sigma(r) < 2 \times 10^{-4}$

Distortion: $|\mu| < 10^{-8}$,

$|y| < 2 \times 10^{-9}$

ROSCOSMOS – MILLIMETRON - "Spectr-M" project

- Cooled 10 meters telescope
- No polarization
- Includes a spectrometer developed in Sapienza
- Inherits the experience of Radioastron
- Detailed science case in http://arxiv.org/abs/1502.06071:
  a. Physics near the galactic center black hole
  b. Formation of stars and planets
  c. Galaxy evolution and cosmology
  d. Investigation of dark energy
  e. Sunyaev-Zeldovich effect on clusters of galaxies up to highest possible distances
  f. Distortions in the CMB absolute spectrum (2.726 Kelvin Black Body)

TABLE 1
MILLIMETRON MISSION REQUIREMENTS

Aperture of the telescope	10m
Aperture ratio	f/7
The telescope wavefront error (RMS)	≤ 10μm (goal ≤5μm)
Telescope temperature	< 10K
Covering wavelength range	20μm ÷ 20mm
Modes of observation	single-dish or element SVLBI system
Total mass	≤ 6600kg
Orbit	L2
Life time	10 years (3-5 years cold phase)
Launch vehicle	Proton

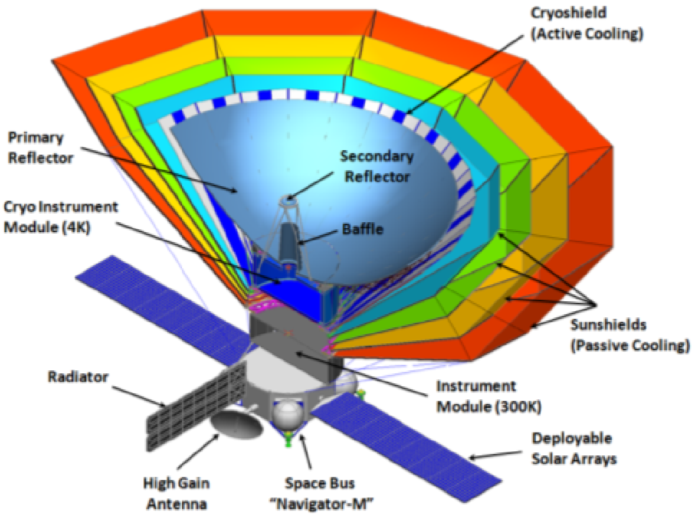


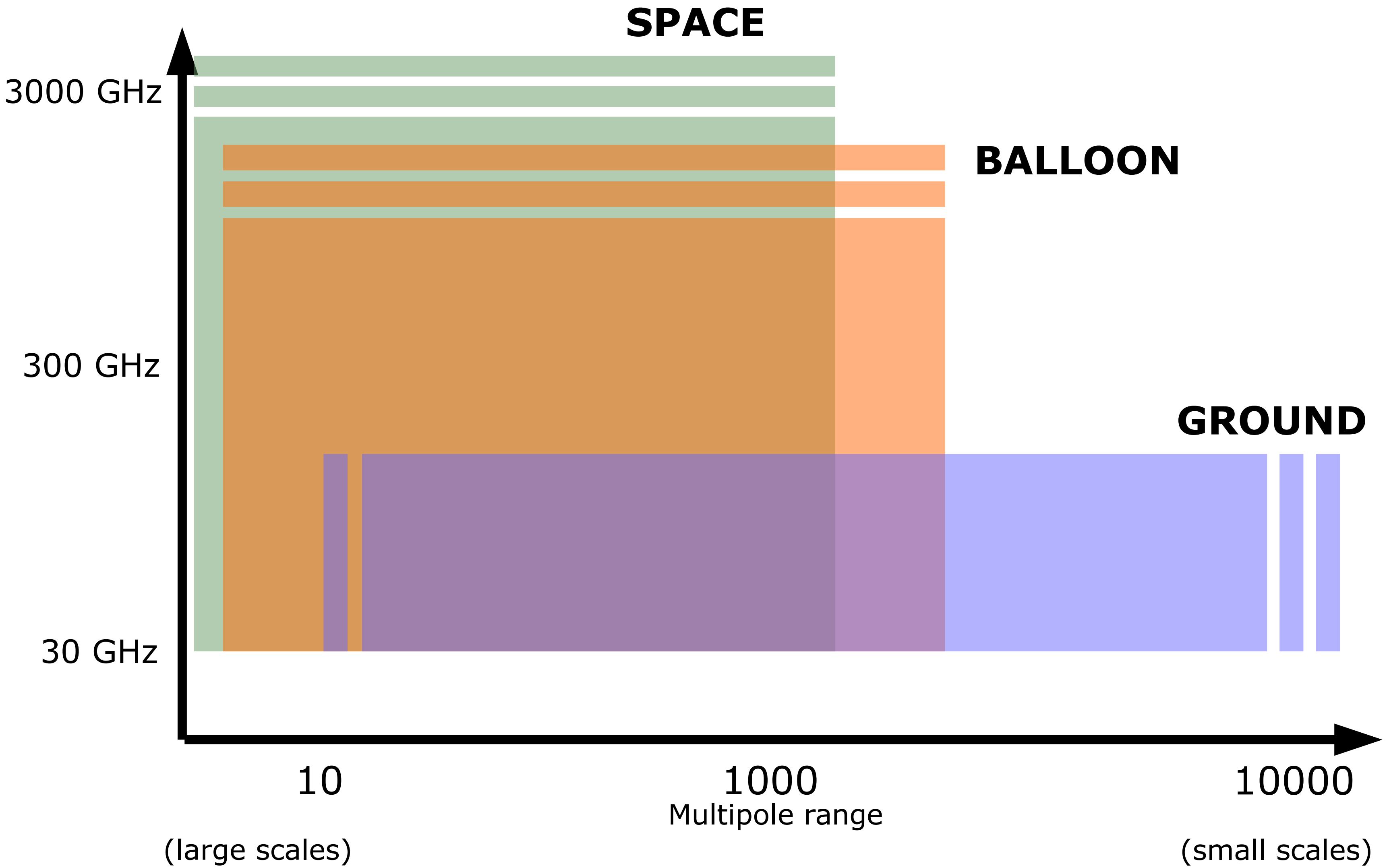
Fig. 1 The conceptual design of the Millimetron

ROSCOSMOS – MILLIMETRON - "Spectr-M" project

European proposals to ESA

See next presentation by P. de Bernardis

The international community effort



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- Space is mandatory for full sky and stability
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- Several different groups are tackling the same scientific target form different prospectives
- The result will be achieved from a community effort